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FINAL PROJECT REPORT

Tools and Materials for Zero Net Energy California Buildings

Edmund G. Brown Jr., Governor
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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Tools and Materials for Zero Net Energy California Buildings is the final report for the Tools and Materials for Zero Net Energy California Buildings project number (PIR-12-032) conducted by the University of California, Los Angeles. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

California has set a goal that by 2020 all new homes should be Zero-Net Energy (ZNE), and by 2030, all new non-residential buildings should be ZNE. To help achieve these goals this project explored new construction materials and developed software tools to help make new or existing residential and small commercial buildings more energy efficient. New user-friendly software tools were developed, including OPAQUE, a tool used to evaluate building envelope performance by calculating U-Value, Time Lag and Decrement Factor for opaque wall or roof assemblies; and SBEED (Small Building Energy Efficient Design), a quick-sketch design tool to help Californians create non-residential buildings that exceed the 2013 Title 24 Energy Efficiency Standard and even to approach ZNE. These two new tools, plus upgraded versions of other popular design tools such as Climate Consultant and HEED (Home Energy Efficient Design), and accompanying tutorials, are available free from the University of California, Los Angeles Energy Design Tools web site.

Keywords: Zero-Net Energy (ZNE), microencapsulated phase change materials (PCM), building envelopes, OPAQUE, SBEED (Small Building Energy Efficient Design), HEED (Home Energy Efficient Design), Climate Consultant

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EXECUTIVE SUMMARY

Introduction

California has set a goal that by 2020 all new homes should be Zero-Net Energy (ZNE), and by 2030, all new non-residential buildings should be ZNE. A ZNE building averages no energy consumption over a year. These ambitious goals can be achieved using energy efficiency measures coupled with renewable energy sources. New construction materials and software tools can help California building owners create highly energy efficient new residential and small commercial buildings, and improve existing ones, even reaching ZNE.

Project Purpose

This project aimed to improve California's building energy efficiency with technological advances in two areas: novel building materials and improved software tools. The work investigated new materials that can help create smart, multifunctional building envelopes to substantially reduce peak and total energy consumption. New software design tools were also created to help building owners reach ZNE targets. Together, these new technological advances can help lower building energy use and peak energy demand in new and existing residential and commercial buildings.

Californians can benefit from free, user-friendly tools, such as on-line tutorials that show how to lower operating costs for energy consumed in homes and commercial buildings, and how to take advantage of new building materials. These tools will encourage Californians to adopt more energy efficient measures to help the state reach its ZNE goals for buildings.

Project Process

The project consisted of an Engineering research team and an Architecture research team. The Engineering team developed and tested a new kind of composite phase change material for ZNE building envelopes. Phase change materials (PCM) store and release large amounts of heat energy as they change between liquid and solid phases. This characteristic can be used to passively reduce heating and cooling loads on buildings.

The Architecture team built or upgraded a suite of software tools for design of ZNE Buildings, including:

- OPAQUE Design Tool, used to evaluate building envelope performance,
- SBEED (Small Building Energy Efficiency Design), a quick sketch design and energy evaluation tool for small, non-residential buildings,
- Climate Consultant to help designers make best use of local climate,
- HEED (Home Energy Efficiency Design) for home design and energy analysis, and

- Tutorials to help users with the software tools.

The two teams integrated their developments at various phases of the project. For example, the Engineering team used the Architecture software tools to retrieve data on California Climate Zones for identifying climate appropriate phase change materials. The Architecture team, when developing the OPAQUE Design Tool, used the models developed by the Engineering team to calculate the performance of innovative construction assemblies using phase change materials.

New Kind of Composite Phase Change Envelope for ZNE Buildings

The team identified existing PCMs, a new generation of building materials, and their properties to help engineers optimize their use in energy-efficient building envelopes. These were compiled into a database and made available on-line at the University of California, Los Angeles (UCLA) website: http://seas.ucla.edu/~pilon/downloads.htm#section4. This will assist builders in selecting appropriate phase change materials to use, based on their phase transition temperatures and heat properties.

The research included evaluating the feasibility of cement-based composite materials containing phase change materials to enhance thermal mass. Thermal mass in a building, comprised of dense materials such as cement, stone or gypsum wallboard, can help store and release heat. PCMs give off heat as the building envelope cools below the PCM melting point, and absorbing heat as the envelope warms above the PCM melting point. Adding phase change materials to building material can provide greater internal temperature stability, even as the outside temperature fluctuates.

The team explored the energy and cost savings potential of phase change materials-composite envelopes in different climates, using numerical models supported by experimental data and climate zone-specific weather information.

Software Tools to Help Californians Design Zero Net Energy (ZNE) Buildings

The most important decisions affecting a building's energy consumption are made at the very beginning of the project by building owners and architects. Energy consultants generally enter the process after these critical decisions have been made. By this point, people have become emotionally invested in their plans and are reluctant to make changes.

Software tools were designed and upgraded to guide Californians in the best ways to improve the efficiency of their homes and commercial buildings. To encourage built-in energy efficiency, the software was designed as a set of user-friendly tools requiring minimal information allowing it to be used by building owners and architects for early project guidance on energy efficiency, when the most important decisions are made. Californians can easily try out variations of alternatives and see visually through graphics how close they come to ZNE. The tools can be downloaded at the UCLA website at: http://www.energy-design-tools.aud.ucla.edu/.

Project Results

New Kind of Composite Phase Change Envelope for ZNE Buildings

Encapsulated phase change materials are weaker and softer than the stone aggregates typically added to concrete. A series of experiments indicated that a tradeoff is made between the increased thermal mass provided by adding phase change materials, and the loss of stiffness and compressive strength because of the soft phase change materials in the mortar. The team created a method to estimate effective thermal and mechanical properties of PCM-mortar composites without requiring time and labor-intensive experimental measurements. In addition, a laboratory method was developed for rapid experimental evaluation of the thermal performance of phase change materials -composite building envelopes.
A critical ratio of stiff quartz to soft PCMs inclusions was developed for design of PCM mixtures to enhance energy efficiency without overly sacrificing mechanical properties.

Simulating climate conditions in a laboratory environmental chamber showed that adding PCMs improved durability by slowing water absorption. The team also identified important criteria based on the results of this study of PCM-mortar composites for limiting thermally-driven expansion and contraction, which can eventually lead to fatigue cracking

The engineering team's analysis and modeling of PCM shows that the annual cooling load reduction by a phase change materials-composite wall, compared with a plain concrete wall, ranged from 85 to 100 percent in Los Angeles and from 53 to 82 percent in San Francisco. The corresponding annual electricity cost savings ranged from $36 to $42 in San Francisco and from $94 to $143 in Los Angeles.

Based on these results from an energy standpoint, the best climate to reduce heat transfer by adding PCM to building walls is one where the daily average temperature remains relatively close to the desired indoor temperature throughout the year, as in Los Angeles. The financial benefit of PCM-composite walls may be maximized in certain climates by careful and creative design choices such as the locating the PCM within the building envelope. The annual cost savings and payback period are region/climate-specific and depend on the structure of electricity pricing implemented by utilities.

The biggest hurdle to widespread use of microencapsulated PCMs in buildings is the cost of these materials. Currently, the cost of bulk microencapsulated phase change materials is more than $10/kg (MicroTek), whereas the other test results estimated the price of PCM must be below $1/kg to ensure a payback period of less than 10 years.

Software Tools to Help Design Zero Net Energy Buildings

The following software tools were developed or upgraded:

- OPAQUE Design Tool is a user-friendly software tool used to evaluate how the properties of heat flow through the opaque parts of the building's envelope (walls and roofs) affect indoor air temperature. With input from the engineering team, the software can predict the performance of a PCM-based high thermal mass composite, and graphically show how this material can help reduce peaks and flatten indoor temperature swings, reducing heating and cooling energy demands.
- SBEED (Small Building Energy Efficient Design) is a quick-sketch design tool to create a non-residential building that meets or exceeds 2013 Title 24 Energy Efficiency Standards. SBEED will compare how closely successive designs approach zero-net energy.
- Climate Consultant is a popular design tool, having been downloaded by more than 100,000 users during the research period. This tool helps consumers understand how to take advantage of their local climate to reduce building energy consumption by displaying a variety of graphic representations of hourly climate data which can be automatically downloaded for thousands of locations. A key feature allows users to determine the best set of climate responsive design strategies and receive a set of Top-20 design guidelines which were updated under this grant to include Non-Residential design guidelines.
- The popular HEED (Home Energy Efficient Design) software was upgraded to meet the 2013 Residential Title 24 Code and to add several new capabilities. A tablet application of HEED was also developed to run on the Microsoft Surface Pro.
- A series of 12 tutorials explaining how to use the various design tools to create ZNE buildings was created and posted on UCLA website. They are designed for everyone from knowledgeable building owners to contractors, builders, architects, and students. These tutorials include the User Hot Line and the HELP function that is available on each screen in all the software, creating a mini-ZNE university for all expertise levels.

The research team is committed to making all software tools developed under this project available free to the public for download from the UCLA Energy Design Tools web site (http://www.energy-design-tools.aud.ucla.edu/). This includes versions of the software for Windows and MAC operating systems and a Microsoft Pro Tablet version of HEED. In addition, numerous supporting documents and tutorials are also available on the web site as well as a Hotline for technical queries. The web site, Hotline and all software developed through this project will be maintained for at least three years after the grant was completed.

In addition to UCLA hosting the tools, they are available at several other websites:

- Facebook: https://www.facebook.com/Energy-Design-Tools-Group-621888581239953/

- Building Energy Software Tools (BEST) directory: - https://www.buildingenergysoftwaretools.com/software/heed-home-energy-efficient-design
- YouTube Tutorials:
    - https://www.youtube.com/watch?v=znoMYDq5T8Y
    - https://www.youtube.com/watch?v=kFhC821aXU8
    - https://www.youtube.com/watch?v=g-pdhm3rClk

Project Benefits

Using the software tools developed in this project, Californians can design more energy efficient buildings and better understand how to use the resources of the local climate for natural heating and air conditioning. For example, natural gas ratepayers using the HEED/SBEED software will see a set of bar charts showing how heating and cooling energy consumption can be reduced by various design alternatives. Climate Consultant will also show a set of graphics of the solar resources available for passive heating in their climate zone. OPAQUE depicts how the design of building envelope can mitigate the heat gain and heat loss of the building. As a result, the natural gas ratepayer's bills can be reduced.

Electric ratepayers using HEED/SBEED will easily see how energy consumption of air conditioning, fans, lights, and appliances can be reduced by designing a more energy efficient building. Climate Consultant provides graphics showing the magnitude of cooling required in their climate and as well as the times when shading is necessary, when wind resources are available for natural ventilation, and the potential for earth cooling. By using these tools to design more energy efficient buildings that use the local climate for natural cooling, the electric ratepayer's bills can be reduced. If SBEED is used on only one percent of newly-constructed or renovated buildings, then it would save 1,778,000 kWh and 31,280 therms annually or the first year's annual savings to ratepayers would be $231,205 for electricity and $21,270 for natural gas —more than $252,000 per year. In the five years following the release of SBEED, the total annual savings for Californians would be about $1.3 million. The total accumulated savings for the first five years should be almost $4 million.

Because HEED/SBEED has a built in carbon calculator, it will instantly calculate and display graphically the greenhouse gas reduction achieved, showing whether a design change has helped produce a Zero-Carbon Building. HEED/SBEED can also quantify the magnitude of the proposed voluntary Reach Standard for Title 24. For example, the programs will easily show whether a design is 15 percent or 35 percent more energy efficient compared to a code compliant building.

Data collected during the past three years show 13,000 downloads of HEED and more than 100,000 downloads of Climate Consultant.

This information will also be made accessible to the media and other resources such as:

- California Building Industry Association at http://www.cbia.org/
- California Building Officials at https://www.calbo.org/
- California Department of Housing and Community Development at http://www.hcd.ca.gov/
- California Community Services and Development at http://www.csd.ca.gov/

CHAPTER 1: Introduction

By the 2020 all new homes in California must be Zero-Net Energy (ZNE), and by 2030 all new non-residential buildings must also be ZNE. These are incredibly ambitious goals. Today many Californians are not even aware of these requirements, and most have no idea of how to achieve them. Project researchers explored new construction materials and developed software tools to help California building owners and ratepayers create energy efficient, new or existing residential and small commercial buildings.

1.1 Project Purpose

This project aims to improve California's building energy efficiency goals through technological advances in two areas, the development of smart, multifunctional building envelopes able to substantially reduce peak and total energy consumption, and the development of new software design tools intended to help building owners reach ZNE targets.

These new technological advances, working together, will help lower building energy use and peak demand in both new and existing residential and commercial buildings. This public interest electric and natural gas research project meets the following criteria:

- Advance science and technology by developing an improved type of building envelope component which increases thermal mass using phase change materials (PCM), and by developing new software tools designed to help all California ratepayers create the most cost effective ZNE buildings without having to hire a consultant.
- Benefit California citizens by making available free, user-friendly tools that show how to lower operating costs by reducing energy consumed in their commercial buildings and homes, and that also show how to take advantage of new building materials of all types.

Clearly this integrated project will increase the adoption of energy efficient measures in California. Specifically, this project is designed to also help California reach its goals of ZNE buildings and to contribute to future revisions of the Building Energy Efficiency Standards.

1.2 Project Process

The project consisted of two separate research teams: an engineering team developed and tested a new kind of composite phase change envelope for ZNE Buildings, as described in Chapter 2. An architecture team built a suite of software **Tools for Zero**

Net Energy Buildings as described in Chapter 3. There was synergy between the two teams at various phases of the project. For example, early on the engineering team used the Architecture software tools to retrieve data on California Climate Zones for identifying climate appropriate PCMs. The primary integration occurred in developing the OPAQUE Design Tool (architecture team) where computational models developed by the engineering team to calculate the performance of innovate construction assemblies using PCMs are incorporated into the software.

Chapters 2 and 3 present an overview of the results of the work of the two teams. Detailed discussions of the work by the Engineering Team have been published in numerous articles which are referred to in relevant sections of this report. All software and related documentation and tutorials developed by the Architecture Team are available for free download from the UCLA Energy Design Tools website.

Chapter 4 covers economic and environmental impacts of the two-pronged approach to energy savings; Chapter 5 explores methods of technology transfer; and Chapter 6 looks at production readiness of the PCM technology and the software delivery.

CHAPTER 2: A New Kind of Composite Phase Change Envelope for ZNE Buildings

The goal of this task was to study and optimize the design of energy-efficient building envelopes containing phase change materials (PCMs). PCMs provide passive reduction of heating and cooling loads on buildings, thanks to their ability to store large amounts of thermal energy in the form of latent heat associated with reversible phase transitions between liquid and solid phases. Through a series of experiments, this task evaluated the various material properties of PCM-mortar composite materials with various PCM dosages in order to provide guidelines to design PCM-mortar composites for building envelopes. This research includes an evaluation of the feasibility of cement-based composite envelope materials containing PCMs (i.e., by assessing the PCMs' effect on the mechanical properties and durability of the cementitious systems).

Research also included an exploration of the energy and cost savings potential of PCM-composite envelopes in different climates, through numerical models supported by experimental data and climate zone-specific weather information. It identified effective approximations which can be used to estimate effective thermal and mechanical properties of PCM-mortar composites without requiring time and labor-intensive experimental measurements.

2.1 Phase Change Materials (PCMs) Compatible with California Buildings and 16 Climate Zones

2.1.1 Aims

- Compile a database of existing phase change materials and their properties
- Identify PCMs suitable for use in California building envelopes

2.1.2 Results

- The research team compiled a database of more than 500 PCMs, including more than 250 commercially available PCMs from various manufacturers.
- The database is available in the form of an Excel spreadsheet from the lab webpage: http://seas.ucla.edu/~pilon/downloads.htm#section4.
- The database was also added to the Wikipedia article on phase change materials: https://en.wikipedia.org/wiki/Phase-change_material

2.1.3 Conclusion

The compiled database will aid in the selection of appropriate PCMs for use in building envelopes in one of California's 16 climate zones. The database can be used in conjunction with design criteria for selection of PCMs based on their phase transition temperatures and thermophysical properties, which are further detailed in Sections 2.2 and 2.3.

2.2 Thermomechanical Properties of PCM-Mortar Walls: Experimental Results

2.2.1 Aims

- Evaluate various material properties of PCM-mortar composite building envelope materials with varying PCM dosages, including:
    - Thermal conductivity
    - Young's modulus (stiffness)
    - Strength
    - Sensible heat capacity and latent heat
- Develop design criteria to appropriately select PCM dosages for PCM-composite building envelopes based on their effect on the thermal and mechanical properties of the composites

2.2.2 Results

2.2.2.1 Thermal Conductivity of PCM-mortar Composites

- The effective thermal conductivity of PCM-mortar composites with up to 30 vol.% PCM was measured using a guarded hot plate apparatus (see ASTM C177-13).
- The effective thermal conductivity was found to be independent of temperature ranging from 10°C to 50°C, despite the occurrence of phase change within this range.
- The effective thermal conductivity decreased with increasing PCM volume fraction.
- Felske's model (2004) showed excellent agreement with the experimental measurements.

2.2.2.2 Young's Modulus and Strength of PCM-mortar Composites

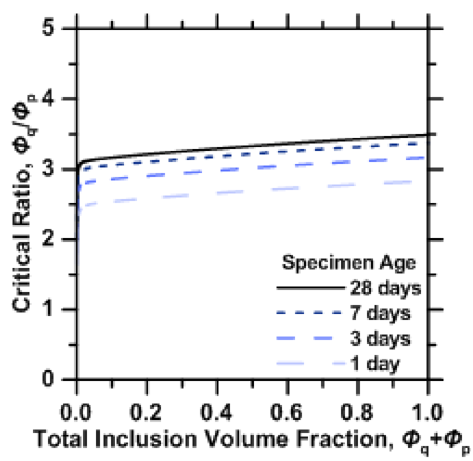
- The compressive strength of PCM-mortar composites was measured and was reduced by approximately 2% for each 1% increase in PCM volume fraction (up to 30 volume % PCM).
- The Young's modulus of cementitious composites containing PCMs (both with and without additional quartz aggregates) was measured as a function of PCM dosage (up to 30 volume %).
- The Young's modulus of PCM-mortar composites was well-described by the Hobbs model (1971).

- When the interfacial transition zone was accounted for, the Young's modulus of mortars containing both PCM and stiff quartz aggregates was well-described by the model of Hobbs, and that of Garboczi and Berryman (2001).
- A critical ratio of dosages of stiff quartz-to-soft PCM inclusions was developed to enable design of PCM mixtures to enhance energy efficiency without sacrificing mechanical properties (Figure 1).
- These results indicated that, in general, quartz inclusions should be present at a level of 2.5 to 3.5 times greater than the PCM volume fraction to produce a composite with a modulus of elasticity equivalent to that of the cement paste. The increase in critical ratio with volume fraction suggests that the PCM-associated interfacial transition zone around the aggregate (ITZ) played a significant role in decreasing the composite stiffness. The results were also strongly dependent on the modulus of the cement paste matrix (including age of matrix), the modulus of ITZ, and the volume of ITZ assumed.
- The results suggest that PCMs exert no detrimental influences, and, in specific cases, even slightly improve the durability behavior of cementitious composites.

2.2.2.3 Sensible and Latent Heat Capacity of PCM-mortar Composites

- The specific heat as a function of temperature as well as the latent heat (enthalpy) of melting and freezing of different commercially available PCMs were measured by differential scanning calorimetry (DSC).
- The peak melting temperatures of different commercially available PCMs were also measured.
- A 25% phase change enthalpy reduction was observed when PCM microcapsules were embedded in cement paste (Figure 2).

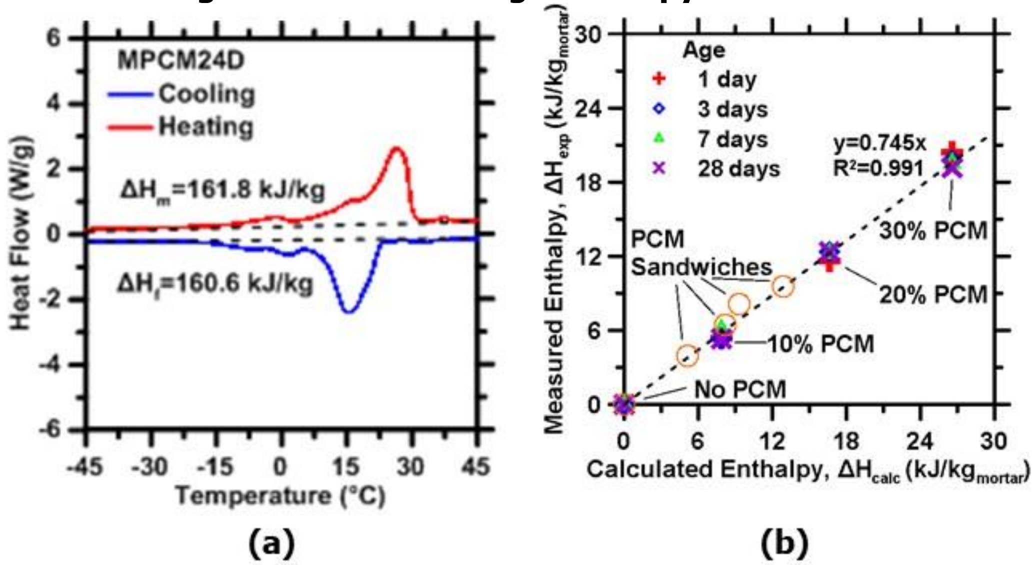
Figure 1: The Critical Ratio of Quartz to PCM



The critical ratio of stiff (quartz) to soft inclusions (PCM) that yields an effective Young's modulus equal to that of the cement paste matrix.

Source: University of California, Los Angeles

Figure 2: Phase Change Enthalpy Reduction



(a) Representative DSC curves illustrating the enthalpy of melting and solidification of pristine MPCM24D and (b) the measured enthalpies of phase change for PCM-mortar composites as a function of the expected enthalpy based on the dosage of PCM.

Source: University of California, Los Angeles

2.2.2.4 Figure of Merit for the Thermal Performance of PCM-mortar Composites

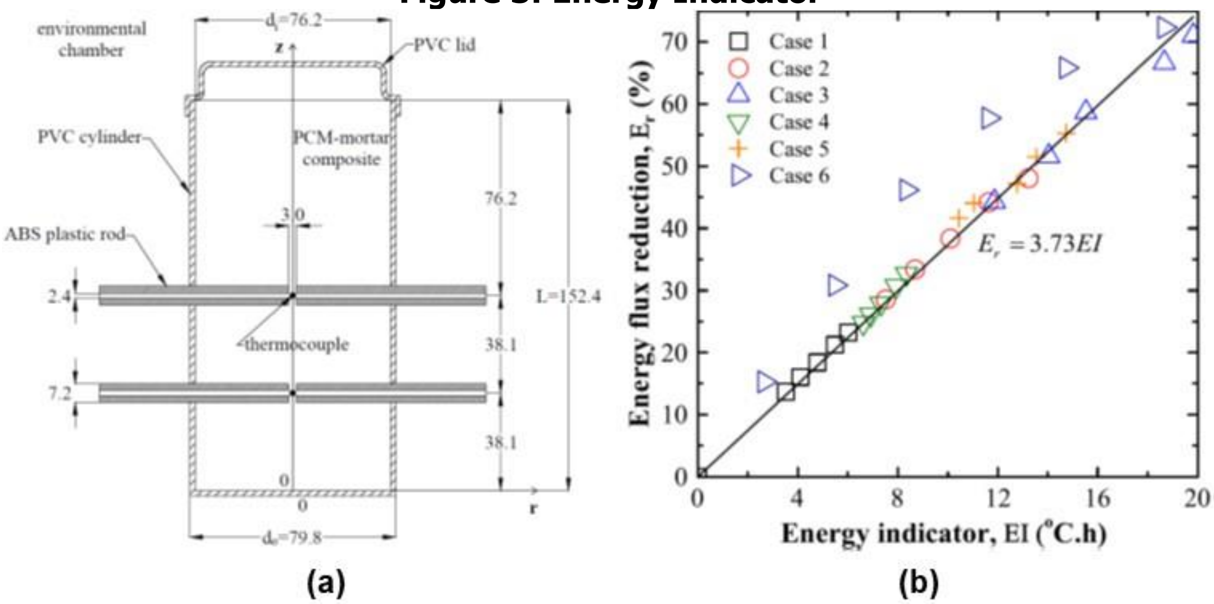
- A novel method for rapid experimental evaluation of the thermal performance of PCM-composite building envelopes was proposed based on a figure of merit dubbed the "energy indicator."
- The energy indicator is calculated by comparing the transient temperature evolutions within cylindrical cement paste specimens with and without microencapsulated PCMs subjected to a linear temperature increase or decrease in a laboratory environmental chamber.
- Good agreement was found between the experimentally measured energy indicator and that predicted numerically using a transient thermal model of the cylindrical specimens.
- As shown in Figure 3, the energy indicator was found to correlate directly to the numerically predicted diurnal energy flux reduction (section 2.3) for a composite wall with equivalent thermal properties.

2.2.3 Conclusion

The results of this sub-task provide guidelines to design PCM-mortar composites for building envelopes. They have also identified effective medium approximations which can be used to estimate effective thermal and mechanical properties of PCM-mortar composites without requiring time and labor-intensive experimental measurements. In practice, a tradeoff must be made between the increased thermal mass and thermal resistance provided by the addition of PCM and the corresponding reduction in stiffness and strength of the mortars. The energy indicator provides a convenient way to rapidly screen PCM-mortar composite building materials in a laboratory setting.

- For further details, see references 22, 23, 24

Figure 3: Energy Indicator



(a) Schematic of a cylindrical PCM-mortar composite specimen used for energy indicator measurements and (b) correlation between the energy indicator of a PCM-composite specimen and numerically predicted diurnal energy flux reduction for a PCM-composite wall with the same thermal properties.

Source: University of California, Los Angeles

2.3 Thermomechanical Models of PCM-Mortar Composites to Design, Optimize, and Control Smart Multifunctional Building Envelopes

2.3.1 Aims

- Develop or identify effective medium approximations (EMAs) capable of predicting the effective thermomechanical properties of PCM-mortar composites (e.g. thermal conductivity, stiffness)
- Develop numerical models to simulate heat transfer through PCM-composite envelopes
- Define performance metrics to evaluate the energy savings potential of PCM-composite envelopes
- Develop criteria for the selection of PCMs for energy-efficient building envelopes and for the optimization of PCM-mortar composite mixture designs

2.3.2 Results

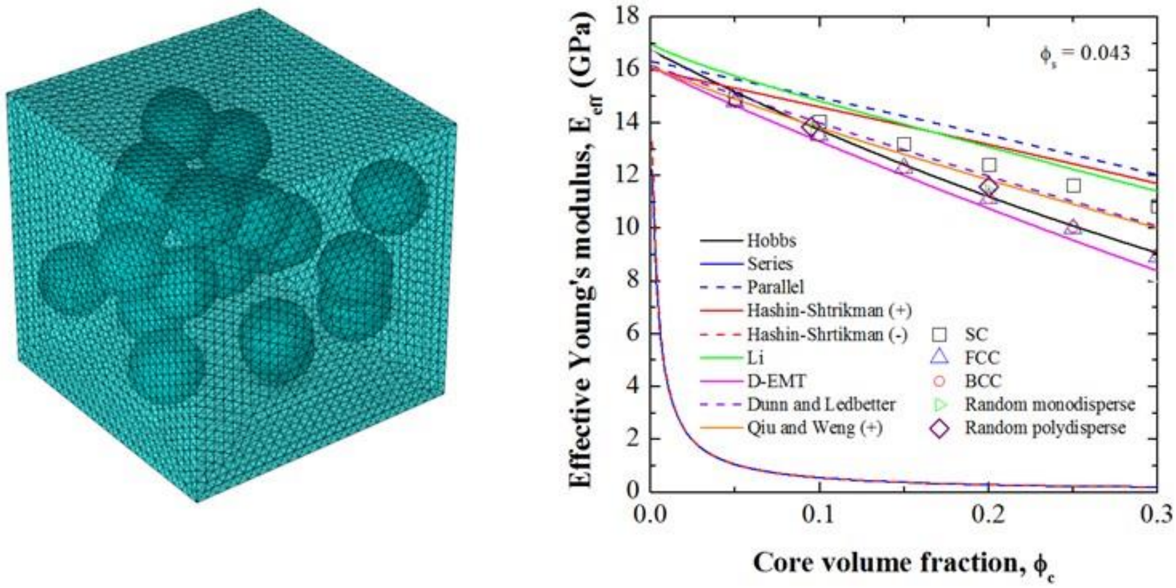
Effective Thermal Conductivity of Composites Consisting of Spherical Capsules in a Continuous Matrix

- Finite element simulations of heat transfer in 3-D microstructural domains were carried out to predict the effective thermal conductivity of three-component composites consisting of spherical core-shell microcapsules in a continuous matrix (e.g., microencapsulated PCM embedded in cement paste).
- The effective thermal conductivity was found to depend only on the volume fractions and thermal conductivities of each constituent material.
- Predictions from Felske's model (2004) agreed very well with the numerical results.

Effective Elastic Properties and Thermal Deformation Coefficients of Three-component Core Shell Matrix Composites

- The finite element approach outlined above was also used to numerically predict the effective elastic properties (Young's modulus, Poisson's ratio) and thermal deformation coefficient (also known as the coefficient of thermal expansion) of three-component composites consisting of spherical core-shell microcapsules in a continuous matrix (Figure 4).
- The model developed by Garboczi and Berryman (2001) agreed well with the numerically predicted Young's modulus and Poisson's ratio.
- The model developed by Hobbs (1971) also showed excellent agreement with the numerically predicted Young's modulus.
- The model developed by Schapery (1968) showed excellent agreement with the numerically predictive effective thermal deformation coefficient of PCM-mortar composites.

Figure 4: Predicting the Effective Properties of Composites



(a) (b)

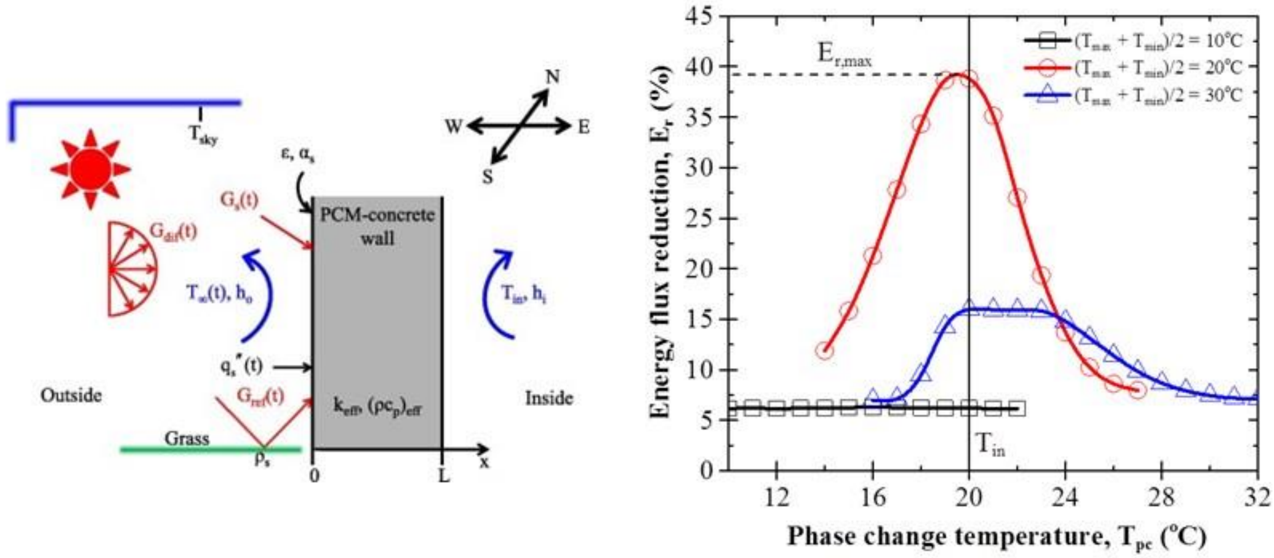
(a) Schematic of a computational cell with randomly distributed microcapsules used to predict the effective properties of composites with spherical microcapsules in a continuous matrix using finite element simulations and (b) effective Young's modulus as a function of core volume fraction predicted numerically as well as by several effective medium approximations (EMAs).

Source: University of California, Los Angeles

Diurnal Thermal Analysis of Microencapsulated PCM-concrete Composite Walls

- Heat transfer through a PCM-mortar composite wall exposed to diurnal outdoor temperature and solar radiation conditions was simulated (Figure 5a).
- The PCM-composite wall could be treated as a homogeneous material with effective thermal properties.
- Including PCM in the concrete wall resulted in a reduction and time delay of the heating load on the building.
- PCM was most effective in moderate climates, specifically those where the outdoor temperature oscillated around the desired indoor temperature.
- A PCM melting temperature equal to the desired indoor temperature resulted in the largest heating load reduction, regardless of outdoor climate conditions (Figure 5b)

Figure 5: Energy Flux Reduction as a Function of the PCM's Phase Change Temperature



(a) **(b)**

(a) Schematic of the transient thermal model used to simulate heat conduction in a PCM-mortar composite wall exposed to the outdoor environment and (b) diurnal energy flux reduction for a PCM-composite wall with 10 volume% PCM as a function of the PCM's phase change temperature.

Source: University of California, Los Angeles

Annual Energy Analysis of Concrete Containing Phase Change Materials for Building Envelopes

- The transient thermal model was used to simulate heat transfer in a PCM-composite wall exposed to realistic weather data over a year in the Los Angeles, CA and San Francisco, California climates.
- The annual cooling load reduction afforded by a PCM-composite wall compared with a plain concrete wall ranged from 85%-100% in Los Angeles and from 53%-82% in San Francisco for PCM volume fractions ranging from 10% to 30%.
- The annual cooling electricity cost savings was as large as $142 for a composite wall in Los Angeles with 30 volume % PCM.
- Energy and cost savings were larger for South- and West-facing walls.

Simple thermal evaluation of PCM-composite building envelopes using the admittance method

- The well-known admittance method (Mackey and Wright, 1943) for determining time lags and decrement factors for building envelopes was modified to account for melting and freezing within PCM-composite envelopes.
- The modified admittance method allows for fast computation of the energy savings potential of PCM-composite building envelopes.

- The modified admittance method will be utilized by the OPAQUE software tool for energy-efficient building design (Chapter 3.1).

2.3.3 Conclusion

The results of the numerical studies on the effective thermal conductivity and thermomechanical properties of PCM-mortar composites provided further guidance for the design of PCM-composite building envelope materials by confirming the ability of effective medium approximations (for example Felske's model) to predict the effective thermal and mechanical properties of PCM-mortar composites. Additionally, the effectiveness of PCM-composite building envelopes in reducing energy consumption and cost for California buildings was evaluated extensively by the diurnal and annual analysis studies. An important design criterion for the selection of PCM melting temperature for maximum energy efficiency was identified. Finally, the modified admittance method provides a means to rapidly evaluate the energy savings potential of PCM-composite building envelope materials and will be a key addition to the QPAQUE software tool.

For further details, see references 25-29.

2.4 Durability of PCM-Mortar Composites Under Simulated Environmental Conditions

2.4.1 Aims

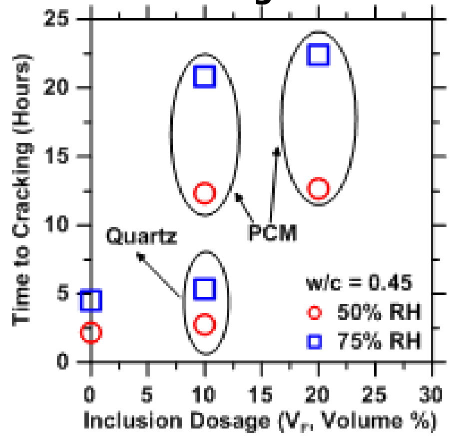
- Assess the durability of PCM-mortar composites under simulated climate conditions in a laboratory environmental chamber
- Determine the effect of PCM addition on the thermal deformation behavior of PCM-mortar composites

2.4.2 Results

Durability of PCM-mortar Composites

- Adding microencapsulated PCM to cement paste induced no change in the tensile strength of the composite material, rather, it increased the time to cracking of cementitious composites.
- PCMs were observed to be non-sorptive inclusions similar to quartz sand when added in a cement paste matrix, slowing water absorption.
- The drying shrinkage of cementitious composites containing PCMs (with and without additional quartz aggregates) was well described by the Hobbs model (Hobbs, 1971).
- Reaction with sulfate ions present in the cement pore solution was determined to be the dominant cause of PCM degradation within cement mortars, rather than breakage due to mixing.

Figure 6: The Time-to-Cracking in a Restrained Ring Test



The time-to-cracking in a restrained ring test from drying initiated at 7 days as a function of the inclusion volume fraction for the cementitious composites PCM or quartz sand inclusions.

Source: University of California, Los Angeles

Thermal Deformation Behavior of PCM-mortar Composites

- The thermal deformation coefficient of cementitious composites with microencapsulated PCM and/or quartz inclusions was measured.
- Adding microencapsulated PCM resulted in an increase of the composite's thermal deformation coefficient.
- A general approach to retrieve the thermal deformation coefficient of the inclusions was developed using the measured effective properties along with Schapery's model (1968), which was previously validated by comparison with numerical simulations (see Section 2.3) and with experimental data from the literature.
- The thermal deformation coefficient of PCM microcapsules was found near that of the shell material, due to the presence of empty space within the microcapsules.
- A design rule was proposed for offsetting the increase in thermal deformation coefficient due to PCM addition by adding hard inclusions (quartz sand) to the cement paste.

2.4.3 Conclusion

This sub-task evaluated the effect of PCM microcapsules on the durability of cementitious composites. The addition of PCM was found to actually improve durability by slowing water absorption. Additionally, important criteria for limiting thermal deformations (which can eventually lead to fatigue cracking) were identified based on the results of the study on thermal deformation behavior of PCM-mortar composites.

For further details, see reference 30 and 31.

2.5 Control Scheme for Integrating HVAC Systems and Multifunctional Smart Envelopes for Thermal Energy Efficiency

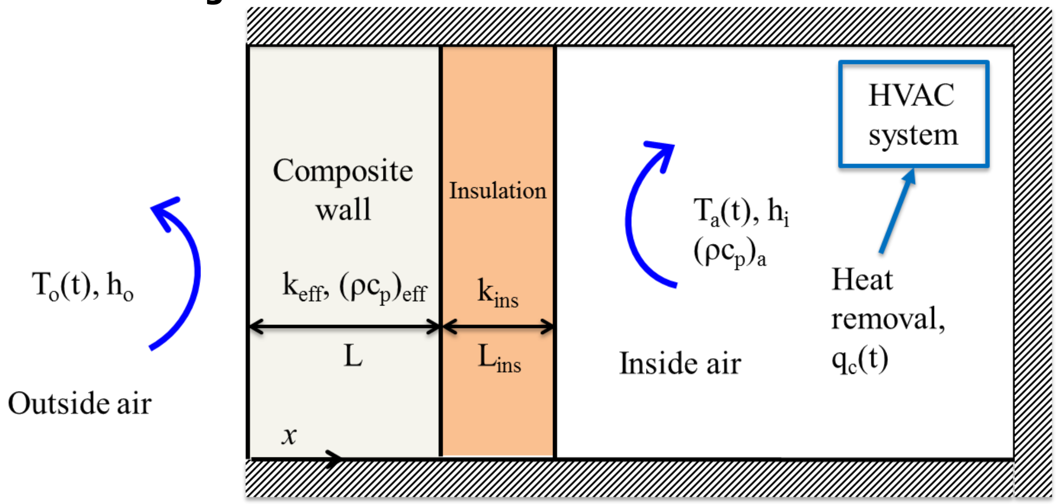
2.5.1 Aims

- Evaluate the performance of existing temperature control strategies when applied to a building with a PCM-composite envelope
- Develop a temperature control scheme to account for the melting and freezing of PCM within PCM-composite envelopes

2.5.2 Results

- A simple thermal model of a room with a PCM-composite envelope was used to assess the diurnal energy consumption and electricity cost associated with cooling the room using various indoor temperature control schemes, including traditional feedback control (such as on/off control, proportional control) and an adapted model predictive control (MPC) scheme (Figure 7).
- The MPC scheme was developed to account for PCM melting and freezing in the wall. This control scheme used future weather predictions as well as predictions of the onset of phase change to determine the optimal heat removal rate to minimize energy consumption over a prediction horizon of two hours.
- The MPC scheme could also instead be programmed to minimize electricity cost over the prediction horizon by considering time-of-use energy pricing and preemptively cooling the room in anticipation of an upcoming peak pricing period.
- A composite wall with 20 volume % PCM reduced the diurnal cooling energy consumption by up to 33% and the diurnal electricity cost consumption by up to 44% compared with a plain concrete wall.
- The MPC control scheme did not provide significant increases in energy or cost reduction compared with a traditional proportional control scheme.
- The reduction in energy consumption by the PCM-composite wall compared with a plain concrete wall was very similar to the passive diurnal energy flux reduction (Section 2.3) when the latter was computed based on equivalent climate conditions.

Figure 7: Schematic of the Thermal Model



Schematic of the thermal model used to evaluate the diurnal energy consumption and cost associated with cooling a single room with a PCM-composite envelope.

Source: University of California, Los Angeles

2.5.3 Conclusion

The results of this Task suggest that the benefit of a PCM-composite envelope lies primarily in the passive heating and cooling load reductions offered by the PCM's latent heat, based on the similarity between the estimated active cooling energy reduction and the passive diurnal energy flux reduction. Also, the absence of extra energy and cost savings provided by the adapted MPC scheme suggest that the gradual process of PCM melting and freezing is adequately handled by traditional feedback control methods. It should be noted, however, that MPC temperature control schemes have shown promising energy-saving capability (Afram, 2013), for example, in handling time-varying set point temperatures or changes in room occupancy, and thus could play an integral role in the operation of energy-efficient buildings.

2.6 Test Cells Constructed of Multifunctional Smart Envelopes With Embedded Adaptive HVAC Control

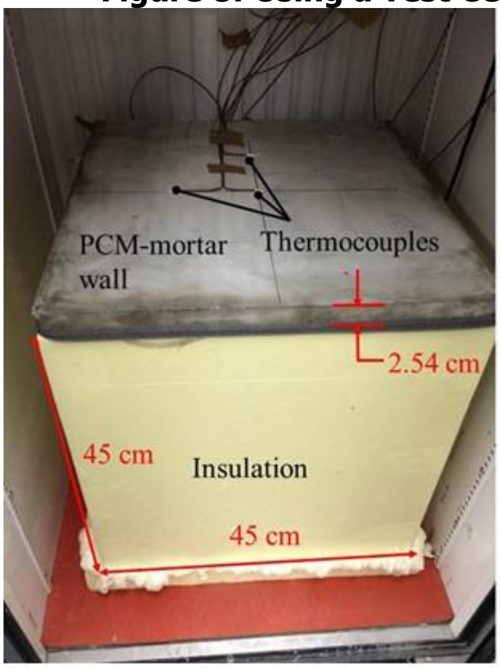
2.6.1 Aims

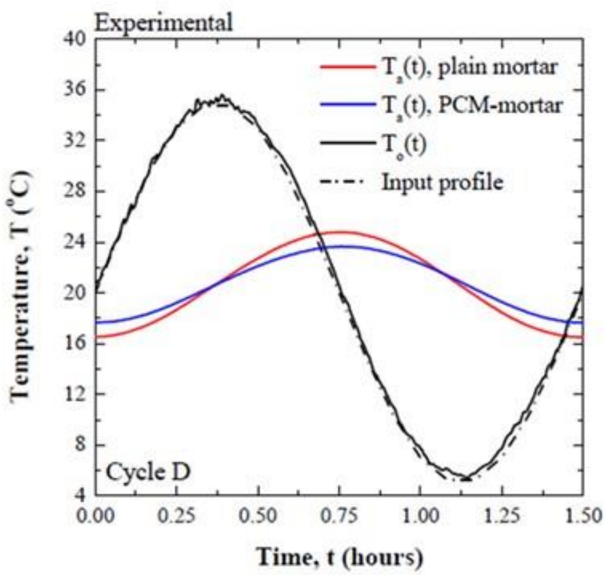
- Construct test cells with PCM-composite walls and evaluate their thermal performance
- Perform scaling analysis to show that small-scale test cells placed in a laboratory environmental chamber can represent the thermal behavior of large-scale building enclosures

2.6.2 Results

- Test cells were constructed with either a plain mortar or PCM-mortar composite wall with 10 volume % PCM.
- The cells were subjected to sinusoidal environmental chamber air temperature oscillations, and the evolution of the indoor temperature was recorded.
- Scaling analysis was used to show that the thermal behavior of the small-scale test cells was representative of a large-scale building enclosure.
- Based on the results of sub-task 2.5, an active control scheme within the test cells was not included (Figure 8).

Figure 8: Using a Test Cell to Evaluate Thermal Performance





(a) **(b)**

(a) Photograph of a small-scale test cell with a PCM-mortar composite wall placed inside a laboratory environmental chamber and (b) evolution of the inside air temperature for a test cell with either a plain mortar or a composite wall with 10 vol.% PCM showing the reduction in inside air temperature amplitude provided by the PCM.

Source: University of California, Los Angeles

2.6.3 Conclusion

The results of this study showed the thermal behavior of building enclosures with PCM-composite envelopes can be accurately captured by representative small-scale test cells placed conveniently in a laboratory environmental chamber. Such small-scale experiments can be used to evaluate the performance of PCM-composite building envelope designs without requiring the large amount of material and available space required to construct a full-scale experimental structure.

For further details, see reference 32.

2.7 Benefits to Ratepayers and Guidelines Deploying Prototypical Multifunctional Composite Envelopes for Residential and Commercial Buildings

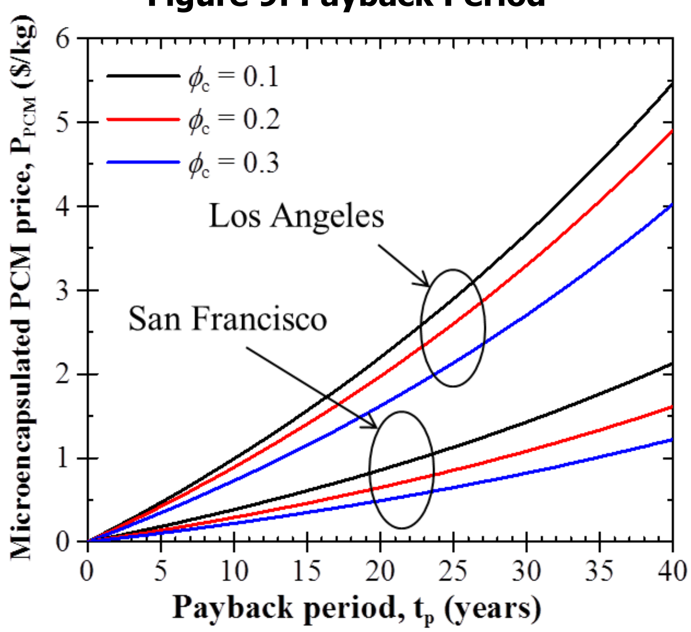
2.7.1 Aims

- Evaluate the benefit of PCM-composite building envelopes to California ratepayers

2.7.2 Results

- Annual cooling load reduction afforded by a PCM-composite wall compared with a plain concrete wall ranged from 85 to 100 percent in Los Angeles and from 53 to 82 percent in San Francisco
- The payback period for the inclusion of 10, 20, or 30 vol.% PCM in a concrete building envelope was estimated based on the predicted annual cost savings (determined through numerical simulation as outlined in Section 2.3) associated with adding PCM to all walls of a typical single-family home in Los Angeles or San Francisco.
- For a given price per unit weight of PCM, the payback period was significantly shorter in Los Angeles than in San Francisco (Figure 9).

Figure 9: Payback Period



Required price of microencapsulated PCM per unit weight as a function of the payback period for composite walls with 10, 20, or 30 vol.% PCM.

Source: University of California, Los Angeles

2.7.3 Conclusion

The estimated payback period, along with the annual electricity cost savings estimates outlined in Section 2.3, provide rough estimates of the economic benefit of PCM-composite envelopes. In practice, the annual cost savings and payback period are highly region/climate-dependent and also depend on the structure of electricity pricing implemented by utilities. The estimated payback period also does not consider other factors such as government subsidies for energy-efficient building materials.

CHAPTER 3: Software Tools for Zero Net Energy Buildings

The result of this task is a set of new software tools that will help persuade ordinary Californians to improve the efficiency of their own commercial buildings and homes, and will show them how to achieve Zero-Net Energy Buildings.

California is not expected to achieve the 2020 and 2030 ZNE goals without new (software) tools that can change the market by making it possible for Californians to become involved, without hiring an energy consultant. The software described are user-friendly tools that will automatically change the mind-set from just barely meeting the Energy Code (creating the worst building legally allowed), to creating the best possible building (using zero-net energy). The most important decisions that affect a building's energy consumption are made at the beginning of the project (on day one) by building owners (not by energy consultants). It is the owners who must reach into their pockets to get the funds to create a ZNE building, so they require tools convincing them this is a good investment. Revising decisions made after day one becomes harder and more expensive as the project moves forward. People become more emotionally invested in existing ideas and are much more reluctant to make changes. These new tools require only the minimal information that is available at the first day of a project, and allow Californians easily try out alternatives to see graphically how close they are getting to ZNE.

3.1 OPAQUE Design Tool: Building Envelope Simulation Tool

3.1.1 Introduction

OPAQUE is a user-friendly software tool used to evaluate Building Envelope Performance by calculating U-value, Time Lag and Decrement Factor for wall or roof opaque surfaces composed of a single or multiple layers of materials. The software integrates aspects of material selection, properties and building design to help Californians create ZNE buildings by showing them how the opaque (none transparent) parts of the building's envelope (walls and roofs) can be designed to modify indoor air temperature. With input from the engineering team, the software can mathematically predict the performance of a PCM-based high thermal mass composite to graphically showing how this material can help reduce peaks and flatten indoor temperature swings reducing heating and cooling energy requirements. OPAQUE also includes a library of traditional construction materials.

OPAQUE runs on either Windows or Mac systems and can be downloaded from:

http://www.energy-design-tools.aud.ucla.edu

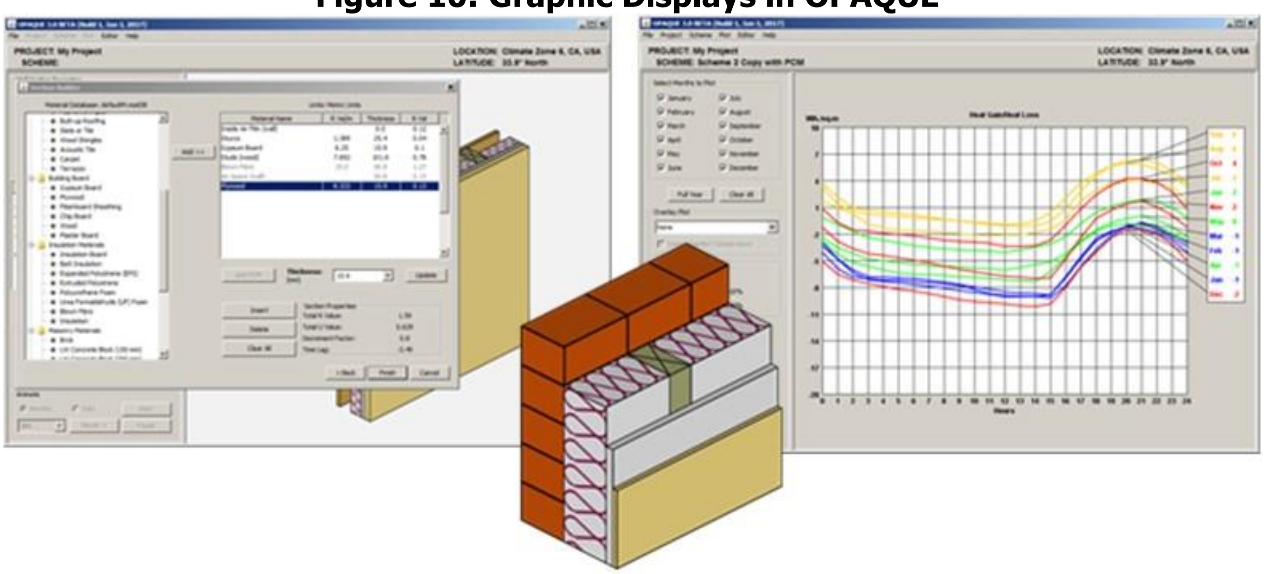
Also available for download on the website is an OPAQUE Tutorial and User's Manual.

3.1.2 Description

Selecting from a library of materials, the user constructs a wall or roof opaque surface in a step-by-step fashion. As each material is added to the composite the total width, total U-value, Time Lag and Decrement Factor are calculated and displayed along with a 3-dimensional model of the section (Figure 10). This calculated data along with temperature and radiation data specific to the project location can be used to determine heat loss and gain through the surface or output to other programs in the UCLA suite. Required climate data can be automatically downloaded from thousands of locations around the world. Once a surface has been designed, it can also be viewed as a 2-D section overlaid by a temperature profile which represents the steady state change in temperature based on each material's contribution to the total U-value for the surface.

In addition, 2-D plots of outdoor and sol-air temperatures, radiation variables, and heat gain/loss through the surface can be displayed. If the user chooses to include a phase change material (PCM) in one of the layers of the surface, a plot estimating the average daily energy reduction for different levels of PCM inclusion is available. OPAQUE includes default material databases in either imperial or metric units largely obtained from the *2013 ASHRAE Handbook* with some additional materials from the *2006 CIBSE Guide A*. The default PCM database included was prepared by the engineering team. Both types of databases can be edited by the user to include new materials or modify properties of existing materials.

Figure 10: Graphic Displays in OPAQUE



Source: University of California, Los Angeles

OPAQUE employs the admittance method (Mackey and Wright, 1944; Milbank and Harrington Lynn, 1974; Pipes, 1957) to calculate the time lag and decrement factor for a surface with multiple layers[1]. These are used to determine the total equivalent temperature difference (TETD) to assess the thermal load through opaque building surfaces. These methods were derived for wall materials with constant thermal properties and not applicable when a phase change material is included. A new algorithm which extends the admittance method to evaluate the thermal load through microencapsulated PCM-composite building surfaces developed by the engineering team is included in the program [2].

3.1.3 Tasks Completed in this Contract

- Developing a graphic user interface which allows the designer to build a composite wall or roof surface from a library of materials.
- Implementing existing algorithms for calculation of the U-Value, Time Lag and Decrement Factor for the composite surface as well as the Heat Gain or Loss through the surface.
- Developing and implementing a new algorithm to predict the performance of a composite building envelope section that can include a layer that contains microencapsulated PCM.
- Graphic display of charts and graphs of data required for calculations as well as measures for evaluating alternative composite sections. One measure of evaluation is the monthly and annual Energy Reduction when PCM is included in a composite layer.
- Compiling a default data bases for standard building material in metric and imperial units as well as a data base for PCM.
- Developing a database editor to enable the user to add new materials to the database or modify properties of existing materials in the database.

3.1.4 Deliverables

- OPAQUE is available for free download on UCLA's Energy Design Tools web site.
- An *OPAQUE TUTORIAL and USER's MANUAL***,** which describes in detail the contents and user interface for this design tool, can be downloaded from the UCLA Energy Design Tools website.
- The paper, *Simple Thermal Evaluation of Building Envelopes Containing Microencapsulated Phase Change Materials Using a Modified Admittance Method*, submitted by the Engineering team, describes the development and implementation of the algorithm when PCM is included in the composite surface.
- The OPAQUE User Email Hotline will be maintained for three more years after the completion of this Contract as posted on UCLA's web site.
- A two-page OPAQUE flyer has been produced.

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[1] *CIBSE Guide A3, Appendix 3.A6* for a description of the calculation method with a worked example.

[2] Thiele, et. Al. 2016, for a discussion of the original admittance method and the extension.

3.2 SBEED: Small Building Energy Efficient Design Tool for Non-Residential Buildings

3.2.1 Introduction

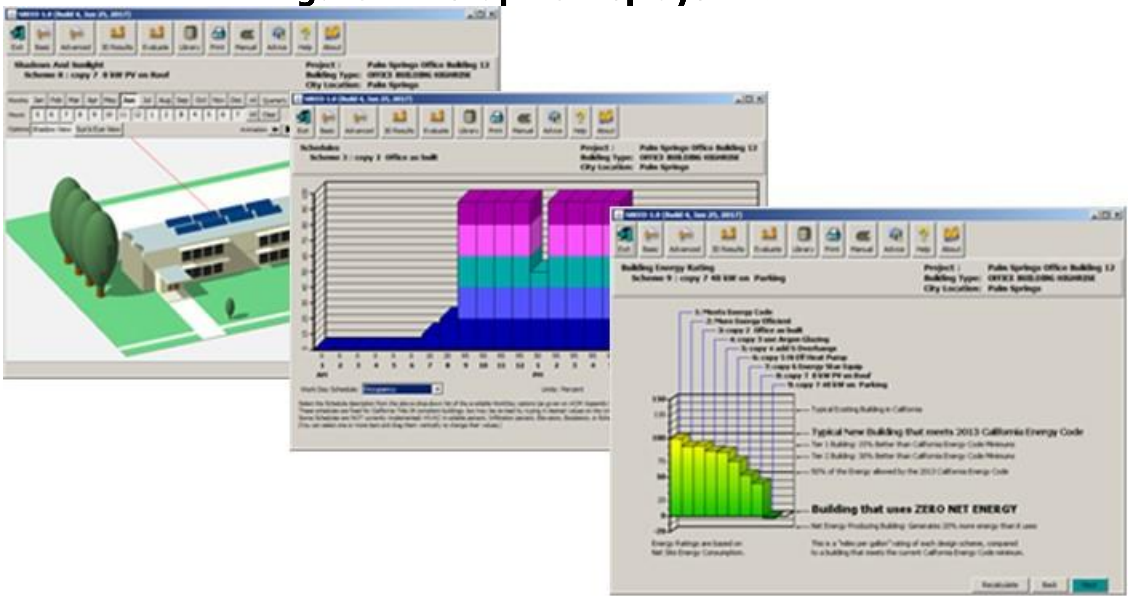
SBEED (Small Building Energy Efficient Design) is a user-friendly day-one quick energy sketch design tool to help Californians create a non-residential building that meets or exceeds the 2013 Title 24 Energy Efficiency Standards for Non-Residential Buildings. SBEED shows a comparison of how close successive designs approach ZNE**.**

SBEED runs on either Windows or Mac systems and can be downloaded from:
http://www.energy-design-tools.aud.ucla.edu

3.2.2 Description

This new easy-to-use Design Tool starts by asking five questions about the project then automatically creates a reference small non-residential building that meets California's 2013 Energy Code. In addition, it automatically creates a second building that is usually about 20% more Energy Efficient. The user can copy either building and revise its design and compare its energy performance with prior versions of up to nine different designs. SBEED (Figure 11) lets the user choose from a variety of building types such as school or office, etc., and displays the 24 hour schedules for a dozen internal loads that define that building type. It automatically generates a floorplan that is free standing or shares common walls, floors, or ceilings. SBEED shows the user graphics of how much energy and money and carbon that can be saved by trying various new Design options or by making Remodeling changes or adding Additions to the existing building. The user can easily modify the floor plan of their building, then click and drag windows to their best location on each wall. The user can add trees and neighboring buildings and see an animation of sun shadows moving across the building. The user can select from lists of standard wall and roof construction or you can input custom details. High mass to temper indoor temperatures can be added. Various other Passive Heating and Cooling options are available including ventilation, evaporative cooling, and passive solar heating. Photovoltaic Panels and Solar Hot Water Collectors can also be added. SBEED can automatically download climate data for thousands of locations around the world. For advanced users there are more detailed design data input options and many kinds of Building Energy Performance displays including bar charts that show how close the building is to Zero Net Energy. SBEED has the same look and feel as HEED (Home Energy Efficient Design) that was originally developed under a prior contract with the California Energy Commission and that was updated as part of this contract (Section 3.4).

Figure 11: Graphic Displays in SBEED



Source: University of California, Los Angeles

3.2.3 Tasks Completed in this Contract

- A new SBEED tool was created that can automatically create Small Non-Residential Building for each of California's 16 Climate zones that meet the 2013 Title 24 Non-Residential Code.
- A new Building Types screen lets the user select from various building types including Assembly, Clinic, Manufacturing, Office, Hotel, Restaurant, Retail, School, or Warehouse.
- The Schedules screen displays the 24-hour usage profiles of the internal loads that define each building type including Occupancy, Lights, Receptacles, HVAC Availability, Service Hot Water, Elevator, Refrigeration, Gas Equipment, Heating Set Point, Cooling Set Point, Infiltration, Escalators, and Water Heater Set Point, and lets users modify these profiles if desired to create custom building types.
- A new Design Options screen lets the user define adjacent surfaces for the automatic floorplan generator, such as common walls with neighbors of shared floors or exposed roofs.
- Windows, Doors, Insulation, Wall Type, Roof, Floor, and Surface Area screens have been modified to allow data input of code-compliant or custom construction assemblies.
- The Solar Systems screen lets users select pre-designed PV (Photovoltaics) systems and SHW (Solar Hot Water) systems, including the Solar Ready Roof Zone (if required) which users can click and drag to place anywhere on the building or on the site.
- SBEED uses the project's zip code to identify the PG&E, SCE, SDGE, or SMUD most widely used non-residential electricity or gas rate, and CO2 Emissions Coefficients.

- Additions and Alteration capabilities were added to support the California Energy Commission's Comprehensive Energy Efficiency Program for Existing Buildings (Assembly Bill 758 [Skinner, Chapter 470, Statutes 2009]), including the ability to predict the performance of Pre-Code and Early-Code Buildings Based on the date they were built (this also supports the California Public Utility Commission's California Solar Initiative program for existing buildings).
- SBEED can model passive strategies like solar gain, natural ventilation, night flushing, and building orientation.
- Thermal Comfort calculation capabilities include a bar chart showing uncomfortable hours (if any), and an automatic direct connection to Climate Consultant to show hourly Relative Humidity and outdoor Air Velocity based on EPW data files, as well as a rank-ordered list of climate specific design guidelines plus a sketch to show how to apply each one.
- For natural ventilation cooling SBEED can show Indoor Air Velocity as influenced by Outdoor Air Velocity, window size and location, and building height.
- An hourly Sun's-Eye-View Graphic Simulation (movie) shows the shading impact of exterior objects like fins and overhangs, tall buildings, shade structures, and trees on windows, PV Panels, and SHW collectors for each hour of each month of the year. This allows SBEED to calculate the reduction in solar gain on each individual window from each individual exterior object.
- SBEED's model for ventilation cooling and night flushing systems of high mass buildings was expanded to include air-to-air heat exchangers (Heat Recovery Ventilators) and evaporative cooling options.

3.2.4 Deliverables

- SBEED as posted on UCLA's web site and available via hot link to many other sites (http://www.energy-design-tools.aud.ucla.edu/).
- Maintain the SBEED User Email Hotline for three years after the completion of this Contract as posted on UCLA's web site.
- Validation Reports of SBEED Performance against ASHRAE Standard 140 and against EnergyPlus using the Commercial Reference Buildings Database will be posted on the UCLA web site.
- Three different SBEED Tutorials are in development and will be posted on UCLA's web site by the completion of this contract.
- A two-page SBEED flyer has been created.

3.3 Climate Consultant: Upgrades

3.3.1 Introduction

Climate Consultant is one of the most popular design tools, downloaded by more than 100,000 users during the time frame of the Contract. This tool helps Californians understand how to take advantage of the resources of their local climate to reduce building energy consumption. This software tool can be downloaded from: http://www.energy-design-tools.aud.ucla.edu

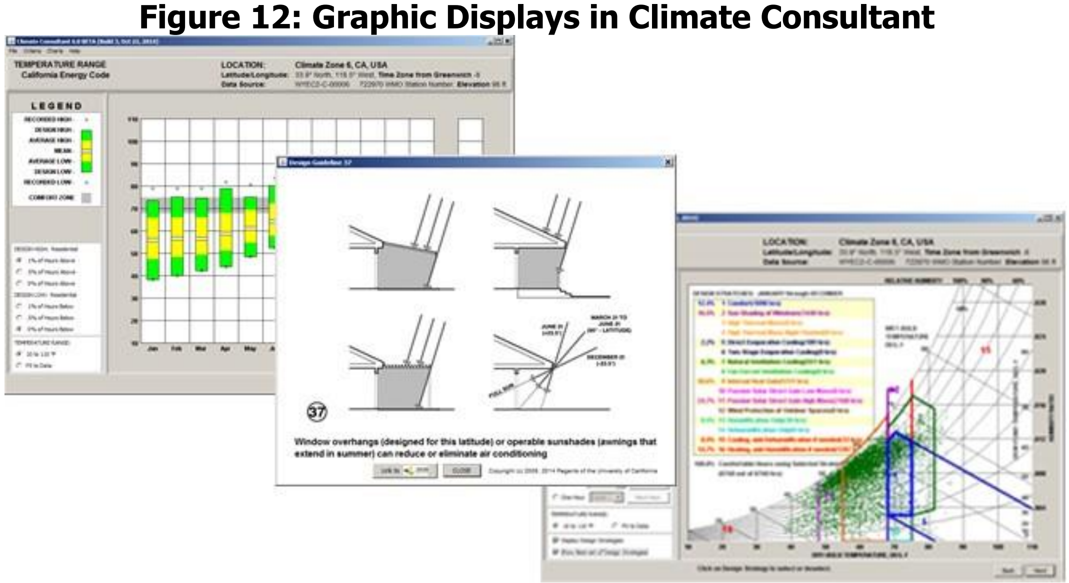
3.3.2 Description

Climate Consultant (originally developed under a prior Energy Commission Grant) displays a variety of graphic representations of hourly climate data which can be automatically downloaded for thousands of locations around the world. The psychrometric chart is the most powerful design tool in Climate Consultant. In addition to plotting the hourly weather data by temperature and humidity, it graphically displays various climate responsive design strategies along with the percentage of hours during the year each could produce comfortable indoor conditions. Types of strategies include, for example, a high thermal mass building with Night Ventilation. Design Strategy Zones are dependent on the user's choice of comfort model from one of the following four:

- California Energy Code Comfort Model, 2013
- *ASHRAE Standard 55 and Current Handbook of Fundamentals*
- *ASHRAE Handbook of Fundamentals Comfort Model up through 2005*
- Adaptive Comfort Model in ASHRAE Standard 55-2010

The user may select a set of Design Strategies or ask Climate Consultant to determine the best strategies for the particular climate. In addition, a Top-20 set of Design Guidelines specific to the climate are presented to the user, each with an accompanying sketch or graphic image to help illustrate the application of this guideline and how it might influence building design (Figure 12).

Figure 12: Graphic Displays in Climate Consultant



Source: University of California, Los Angeles

The primary goal for this Contract was to upgrade Climate Consultant for *2013 Title 24 Residential Code* and add Non-Residential Design Guidelines. In addition, a number of other improvements and enhancements were made to the software as listed in the task activities below.

3.3.3 Tasks Completed in This Contract

- Users may now select whether they are designing Residential or Small Non-Residential buildings. This influences the Top-20 Design Guidelines generated. The heuristic procedure for generating the guidelines was fine-tuned. A major addition to Climate Consultant is a link between the guidelines and supporting examples available on the 2030 Palette (http://www.2030palette.com), a free educational platform containing a set of guiding principles, information and resources—or Swatches—for planning and design of sustainable environments.
- All four comfort models represented in Climate Consultant were tested and modified to meet the latest comfort criteria. Users may now change any of the parameters defining the Comfort and Design Strategy Zones on the Psychrometric Chart.
- A data transfer option was incorporated in the program which allows users to output selected weather data with associated statistics generated by Climate Consultant to a CSV file. This allowed the Engineering team to access weather data needed for their task.
- A graphic input screen for selecting the California Climate Zone EPW data using a map image or by entering the ZIP code of the location was developed.
- With a new Custom Plot Option, users may now design and display their own plots of available EPW weather data and associated statistics. Up to two plots per window may be displayed with two axes per plot. Data can be shown on a monthly, daily or hourly basis.
- In response to user queries during Year 3, it was determined that the website HEED and Climate Consultant linked to for downloading weather data was no longer available. Significant development effort was required to implement and test a new automatic EPW file download procedure for the EnergyPlus site: https://energyplus.net/weather .

3.3.4 Deliverables

- Climate Consultant is posted for free download on UCLA's Energy Design Tools web site.
- Two different Climate Consultant Tutorials have been posted on UCLA's web site.
- Maintain the Climate Consultant User Email Hotline for three years after the completion of this Contract as posted on UCLA's web site.
- A two-page Climate Consultant flyer was created.

3.4 HEED (Home Energy Efficient Design) Tool: Upgrades

3.4.1 Introduction

The goals of this task were to update the popular HEED software (developed under a previous Energy Commission grant) to meet the 2013 Residential Title 24 Code and to add several new capabilities. A copy of HEED can be downloaded from:

http://www.energy-design-tools.aud.ucla.edu

For a graphic demonstration of HEED, three on-line tutorials are also available (in English and Spanish):

View HEED Overview Tutorial (~20 min.)
(Also available in Spanish)

View HEED Basic Design Tutorial (~30 min.)
(Also available in Spanish)

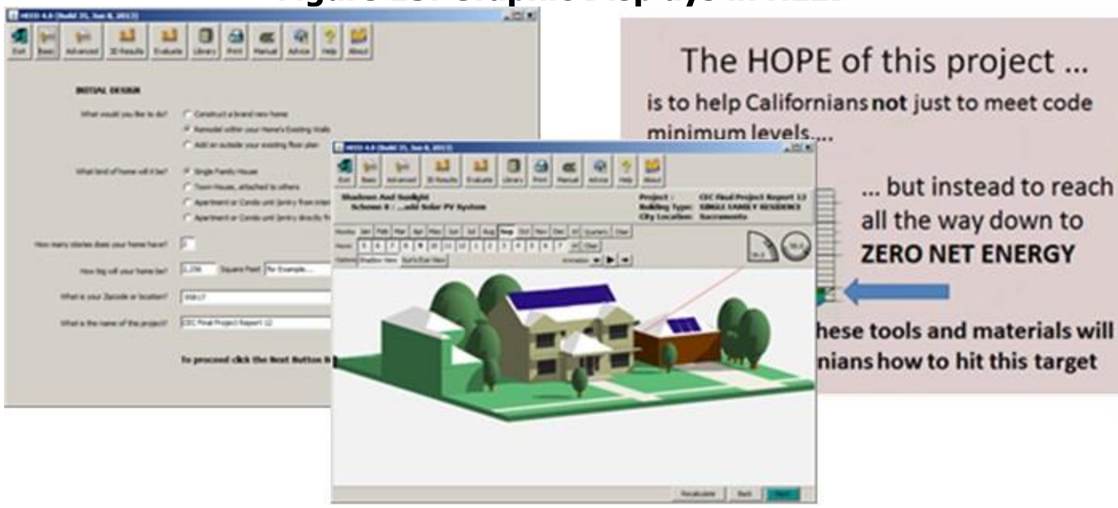
View HEED Advanced Design Tutorial (~37 min.)
(Also available in Spanish)

3.4.2 Description

HEED (Home Energy Efficient Design) is an easy-to-use Design Tool which starts by automatically creating a reference house that meets California's 2013 Energy Code. It then creates a second home that is about 30% more energy efficient. If this is a Remodeling project, then the second reference home HEED creates is for the year of its original construction. The user can design and compare up to nine different homes. HEED displays graphics of how much energy and money and carbon can be saved by trying various new Design options or by making Remodeling changes to their home (Figure 13). The user can easily draw in the actual floor plan of their house, then click and drag windows to their best location on each wall.

Users can add trees and neighboring buildings and see an animation of sun shadows moving across the building. The user can select from lists of standard wall and roof construction or can input custom details. High mass to temper indoor temperatures can be added. Various other Passive Heating and Cooling options are available including natural ventilation, evaporative cooling, and passive solar heating. Users can add Photovoltaic Panels and Solar Hot Water Collectors. HEED can automatically download climate data for thousands of locations around the world. Many kinds of Building Energy Performance data are displayed including bar charts that show how close the building is to Zero Net Energy. For Advanced Users there are more detailed data input options and output display graphics. HEED self-installs on non-networked Windows or Mac systems. A new Tablet version of HEED is also available to run on the MS Surface Pro.

Figure 13: Graphic Displays in HEED



Source: University of California, Los Angeles

3.4.3 Tasks Completed in This Contract

- HEED was upgraded to meet the 2013 Title 24 Code in order to automatically create Standard Design Homes for each of the 16 California Climate zones.
- The Photovoltaics System components catalog and accompanying calculations were initially revised and rewritten to coordinate with updates in Energy Commission-PV. Also the graphic user interface was enhanced to allow click and drag placement of panels anywhere on site including on roofs of any shape. Performance can be calculated for any of eight idealized PV systems ranging in size from 1 to 8 kW, or the option of the Solar Ready Roof Area. Because the Energy Commission-PV catalog is constantly changing, direct link was added to automatically install Energy Commission-PV to allow the user to directly access actual performance using currently approved panels and inverters, and then compare the results with HEED's example systems (note that HEED uses the same algorithms as Energy Commission-PV).
- HEED was upgraded with each electric utility's most widely used 2013 electricity rates and CO2 Emissions Coefficients (currently HEED's zip code input automatically selects the appropriate PG&E, SCE, SDGE, SMUD utility rates and CO2 emission coefficients).
- Algorithms have been updated for various passive cooling options, including calculating the hourly performance of very low energy cooling systems, and HEED's current model was expanded for whole-building economizers and night flushing systems, air-to-air heat exchangers (heat recovery ventilators), various evaporative cooling options, and other very low energy cooling options.
- An automatic link was established to Climate Consultant to generate a list of the Top-20 Design Guidelines based on an analysis of the specific climate data. This tells users which building design options are likely to have the highest payoff in energy and GHG savings.

- Roof Geometry Options in HEED include gables, pitched, and sheds in various combinations (including graphics of roof shape, type, slopes, orientations, and materials).
- Additions and Remodeling capabilities of HEED were expanded to support the Energy Commission's Comprehensive Energy Efficiency Program for Existing Buildings (AB 758), including the ability to predict the performance of Pre-Code and Early-Code Homes based on the date they were built (this supports the CPUC's California Solar Initiative program for existing homes).
- Although not required for the CalGreen Code, HEED's energy and GHG calculation capabilities can model passive solar gain, night flushing, and building orientation, in addition to other capabilities for calculating PV and SDHW systems (as discussed in the AB758 Scoping Report).
- The finalized OPAQUE program generates data which users can import to HEED (including U factor, Time Lag, and Decrement as input on the Surface Area screen).
- HEED's Performance against ASHRAE Standard 140 and against EnergyPlus for HERS Best Cases were validated in a report published in October 2012 and posted on the HEED web site. This report demonstrates that HEED meets Standard 140 matching EnergyPlus performance. The HEED internal computation engine (known as SOLAR5) has not been changed from a theoretical point of view since then, and neither test depends on California Code specific test cases.

3.4.4 Deliverables

- The most recent updates of HEED have been posted on UCLA's web site and are available via hot link to many other sites. HEED is currently available on the Energy Commission web site http://www.energy.ca.gov/research/buildings/wholebuilding.html.
- Six different HEED Tutorials have been posted on UCLA's web site.
- Posted on the Energy Tools Web Site are the 2012 Validation Reports of HEED Performance against ASHRAE Standard 140 and against EnergyPlus using the Commercial Reference Buildings Database.
- The HEED User Email Hotline will be maintained for three more years after the completion of this contract as posted on UCLA's web site.
- A two-page HEED flyer has been produced.

3.5 Tablet Application of HEED

3.5.1 Introduction

The goal of this task was to demonstrate that the HEED software can be rewritten for use on tablets or other hand-held mobile devices, to allow its use in the field or on-site. A copy of HEED for the MS Surface Pro Tablet can be downloaded from:

http://www.energy-design-tools.aud.ucla.edu/heed/

All of the features and input and output screen options of the laptop version of HEED Build 22 are available in this tablet version of HEED. For a detailed explanation of HEED and its many options see Section 3.4 in this report.

HEED self-installs as a stand-alone program on Microsoft Surface Pro Tablet PCs (Windows Surface Pro 3 Tablet or newer). The user should not download this tablet version onto their laptop or desktop because the Tablet Graphical User Interface (GUI) is only intended to run on the hand-held machine. The user can, however, transfer Project Files between these various types of machines.

3.5.2 Description

HEED users requested that a version of HEED be developed that could run on hand-held tablets. There are many potential applications. For example, a tablet version will allow architects to take a fully functional copy of HEED into the field, enabling direct data input when surveying an existing home remodeling project. Developers will be able to show homeowners on-site the energy and cost implications of various options they are proposing and it will allow contractors to meet with suppliers to quickly run calculations to evaluate the performance of alternative materials or equipment options.

At the beginning of this three-year contract there was no hand-held system with the computational power and graphic capability needed to handle the software demands of HEED. Fortunately, when Microsoft released the Surface Pro 3, it was not necessary to strip any of the more computationally intensive or graphically demanding components of HEED. Other systems with similar power from other manufacturers will undoubtedly soon follow.

Certainly it appears that mobile apps will play a major role in the use of Building Energy Efficiency Tools in the future.

3.5.3 Tasks Completed in This Contract

It was successfully demonstrated that a functional version of HEED Build 22 can be installed and run on a Microsoft Surface Pro 4 tablet. A Beta Test version was posted on the UCLA EnergyDesignTools web site.

3.5.4 Product Status

The MS Surface Pro does not have a totally mature operating system, because problems of screen scaling were discovered on different models of Surface Pro. In HEED there are at least ten different types of screen designs (text panels and graphics) that each show up in different sizes (scales) depending on the model of tablet. The team attempted to find a universal scaling solution that will work automatically across all platforms and they anticipate this problem will be solved shortly by Microsoft. If it happens before the end of this contract, the scaling solution will be posted an updated public release version on the EnergyDesignTools web site.

3.5.5 Deliverables

- The Public Beta Test version of the Tablet Application for HEED has been posted on the Energy Design Tools web site:
  http://www.energy-design-tools.aud.ucla.edu/tablet/request-heed.php
- Because this Tablet version is a fully functional version of HEED, the six different HEED Tutorials that have been posted on UCLA's web site apply directly.
- The HEED User Email Hotline will be maintained for HEED Tablet users for at least three years after the completion of this Contract.
- A two-page HEED (Home Energy Efficient Design) descriptive flyer has been produced that includes information about its features, capabilities, uses and accessibility to the public, all of which are available on the HEED Tablet version.

3.6 On-Line Tutorials to Help Californians Create Zero Net Energy (ZNE) Buildings

3.6.1 Introduction

Twelve tutorials explaining how to use the various design tools were developed as part of this contract to create ZNE (Zero Net Energy) buildings and posted on UCLA's website. They are designed for everyone from knowledgeable building owners to contractors, builders, architects, and students. These tutorials will meet the demand for technology transfer and, together with the User Hot Line and the HELP function that is available on each screen in all the software, they create a mini-ZNE university for Californians.

3.6.2 Description

To help the greatest number of Californians understand how to create zero net energy buildings a dozen on-line YouTube or text-based tutorials were produced. In past contracts this need was attempted to be met by offering free workshops in various locations around the state. However, the team was only able to reach a few hundred people. Instead tutorials were produced and posted so that users can access them from anywhere in the state (or in the world for that matter), and at any time that is convenient to them. Three of these tutorials offer Spanish to support an even greater number of Californians.

3.6.3 Tasks Completed in This Contract

Nine YouTube tutorials for HEED and Climate Consultant, and one text based tutorial for OPAQUE have already been developed and posted. Two more YouTube tutorials for SBEED are currently being developed and will be posted before the end of this contract.

3.6.4 Deliverables

- The following YouTube tutorials were developed and posted on the EnergyDesignTools web site:
  - View HEED Overview Tutorial (~20 min.)
  - View HEED Basic Design Tutorial (~30 min.)
  - View HEED Advanced Design Tutorial (~37 min.)
  - View Climate Consultant Overview Tutorial (~10 min.) authored by Carmen Trudell
  - View Climate Consultant Advanced Tutorial (~20 min.) authored by Carmen Trudell
  - View Psychrometric Chart Tutorial (~4 min.) authored by Yasmin Bhattacharya
- Three Spanish Language YouTube tutorials were also developed and posted, authored by Jose Manuel Almodovar, from the University of Seville (Spain):
  - View in Spanish HEED Overview Tutorial (~20min)
  - View in Spanish HEED Basic Design Tutorial (~30min)
  - View in Spanish HEED Advanced Design Tutorial (~37min)
- One text based tutorial on Opaque has also been posted
  OPAQUE Tutorial and User's Manual
- Three other YouTube tutorials are currently in development for SBEED and will be posted before the completion of this contract:
  - View SBEED Overview Tutorial (~20 min.)
  - View SBEED Basic Design Tutorial (~30 min.)
  - View SBEED Advanced Design Tutorial (~37 min.)
- A two-page Tutorial flyer has been produced and can be found on the UCLA website.

CHAPTER 4: Data Collection and Analysis

The goals of this task were to collect operational data and analyze the data for economic and environmental impacts.

4.1 Economic and Environmental Impacts of Phase Change Materials

This project examined the annual energy and cost savings potential of adding microencapsulated phase change material to the exterior concrete walls of an average-sized family home in California climate zones 3 (San Francisco, California) and 9 (Los Angeles, California). The annual energy and cost savings were larger for South- and West-facing walls than for other walls. They were also the largest when the phase change temperature was near the desired indoor temperature. The addition of microencapsulated phase change material to the building walls reduced the cooling load in the summer substantially more than the heating load in winter. This was attributed to the cold winter temperatures resulting in nearly unidirectional heat flux on many days. The annual cooling load reduction in an average-sized single family home in San Francisco and in Los Angeles ranged from 85% to 100% and from 53% to 82%, respectively, for phase change material volume fraction ranging from 0.1 to 0.3. The corresponding annual electricity cost savings ranged from $36 to $42 in San Francisco and from $94 to $143 in Los Angeles. From an energy standpoint, the best climate to reduce heat transfer by adding PCM to building walls is one in which the daily average temperature remains relatively close to the desired indoor temperature throughout the year, as in Los Angeles [3].

Between 1990 and 2005, the average annual electricity cost for residential customers in San Francisco and Los Angeles was about $840 and $600, respectively. Thus, the annual cost savings incurred by adding 20 volume % microencapsulated PCM to concrete walls represented about 5% and 22% of the annual electricity expenditures in San Francisco and Los Angeles, respectively. Interestingly, the total annual cost savings achieved by including microencapsulated PCM only within the South- and West-facing walls was only slightly smaller than that for four walls in San Francisco. This can be attributed to the very small annual cost savings for the North- and East-facing walls in San Francisco. On the other hand, annual cost savings were substantially smaller in Los Angeles when microencapsulated PCM was included only within the South- and West-facing walls. This suggests that the financial benefit of PCM-composite walls may be maximized in certain climates by careful and creative design choices such as the

[3] Thiele, et. Al, 2015, for more details of the analysis

location of the PCM within the building envelope. To explore cost savings further, the material and implementation costs of PCM should be considered along with any incentive policies to assess the payback period for different PCM-composite building envelope designs.

4.2 Economic and Environmental Impacts of Software Tools

As part of this project, a system was developed and implemented which keeps track of the "hits" on the UCLA Energy Design Tools website and counts downloads for each of the software programs developed or modified under this contract. Data collected to date shows almost 13,000 downloads of HEED and more than 100,000 downloads of Climate Consultant over the past three plus years. There have been more than 3,000 views of the HEED YouTube Tutorials and more than 4,000 views of the Climate Consultant tutorial. In the three months since the Beta version of SBEED has been available for free public distribution on the website there have been a few dozen downloads and also a few dozen downloads of the HEED Tablet version. Data during the next three years will be collected for these programs as well as for the newest program, OPAQUE, which was recently posted.

Combined, this suite of programs, which are free to the public, has achieved significantly greater market penetration than anticipated. The goal has been to get these powerful new design tools into the hands of as many Californians as possible to galvanize the widest possible public effort toward achieving the AB32 goals.

Although use is just beginning, the "market" for SBEED is potentially quite large. For example, Commercial End-use Data shows more than 4.9 billion square feet of commercial floor space in California. It is assumed only about 52% of this is for small commercial buildings (Small Office, Restaurant, Retail, Food Service, Unrefrigerated Warehouse, School, and Lodging) (Att 17, PON-12-503). This represents more than 2.5 billion square feet of floor space.

Using SBEED it is currently very easy to make changes that show a 15% reduction in total energy consumption, and a 35% reduction is quite achievable with standard technology and design options, which are similar to the current Title 24 Reach Standards. Remembering that the goal of this Program is to produce Zero Net Energy, it is safe to assume that building owners who use SBEED in the coming years will average of 50% increase in building energy efficiency. Currently these small commercial buildings use about 35,570 GWh/year of electricity and 625 million therms of gas (Table 8-1 and 8-2, Att17, PON-12-503). Assuming safely that the life of commercial buildings is 100 years, then every year one building in every hundred will need to be either built new or retrofitted. And if it is assumed that SBEED is used on only one in a hundred of these new construction or retrofit buildings then it would save 1,778,000 kWh and 31,280 therms annually. Using commercial utility rates of $0.13/kWh and $0.68/therm, the first year's annual savings to ratepayers would be $231,205 for electricity and $21,270 for gas, for a total of over $252,000 per year.

In the five years following the release of SBEED, the total annual savings for Californians will be about $1.3 million (Table 1). The total accumulated savings for the first **five** years should be almost $4 million.

Table 1: Calculation of Total Savings from Using SBEED Over Five Years

Year	Current Year's New Projects will Save	Prior Years' Projects Continue to Save	Total Savings in California for this Year
2017	$252,000		$252,000
2018	$252,000	$252,000	$504,000
2019	$252,000	$504,000	$756,000
2020	$252,000	$756,000	$1,008,000
2021	$252,000	$1,008,000	$1,260,000
Total Savings in California over 5 years:			$3,780,000

Source: University of California, Los Angeles

These assumptions are quite conservative because if the goals of AB32 gain widespread support, then SBEED probably could have much more than 1% market penetration (remembering that existing certified compliance tools already now have about 90% market penetration). Very few California commercial buildings last more than 100 years, so this assumption also seems conservative. There undoubtedly will be inflation in energy costs which would increase Total Savings. If SBEED helps gain wide spread support for AB32 then energy savings will be closer to zero net energy and the dollar savings will be much greater. This analysis also assumes that all of the savings from this project comes only from SBEED, but clearly information generated by the other components will in fact add value to Californians and will help them to reduce building energy consumptions.

There are also a number of benefits which cannot be economically quantified. One is the fundamental research on PCMs that can help change the way Californians see the benefits of thermal storage in the design and construction of their buildings. SBEED and HEED will make the benefits of thermal mass graphically apparent. A recently published study by one of the PIs showed that air conditioners could be eliminated from new homes in eight of California’s sixteen climate zones if thermal mass and night flush cooling were used correctly (Milne 2005).

Another qualitative benefit is that all the design tools are extremely popular with students. They have been used in graduate building science courses at Berkeley, USC, and both Cal Polys. Climate Consultant is also used by a wide range of other disciplines including geology, urban planning, and real estate. Thus this project is helping to prepare the next generation of Californians to use these types of tools as a matter of course from the beginning of their careers.

The researchers believe the internet-based tutorials for the developed software will be used by many Californians and will help them understand the issues in building energy efficiency, even if they do not actually use this software

CHAPTER 5: Technology Transfer

5.1 Technology Transfer Relating to Phase Change Materials

Numerous articles describing the results of the various tasks undertaken by this contract have been published by the engineering team or have been submitted for publication. They are listed in sections 2.2.3, 2.3.3, 2.4.3 and 2.6.3 of this report and are currently available or will be available for access by other researchers, decision makers or the general public.

In addition, as detailed in section 2.1 of this report, a database of more than 500 PCMs, including 250 commercially available PCMs from various manufacturers was prepared and is available for public access.

- The database can be downloaded in the form of an Excel spreadsheet from the following engineering lab webpage: http://seas.ucla.edu/~pilon/downloads.htm#section4.
- The database was also added to the Wikipedia article on phase change materials: https://en.wikipedia.org/wiki/Phase-change_material

Finally, the MATLAB software tools developed by the engineering team to estimate thermal performance (by the Energy Indicator concept described in Task 2) and mechanical properties of PCM-composite building materials will be made available upon request.

5.2 Technology Transfer of Software Tools

The Energy Design Tools team at UCLA is committed to making all software tools developed under this project available free to the public for download from the UCLA Energy Design Tools web site (http://www.energy-design-tools.aud.ucla.edu/). This includes versions of the software for both Windows and MAC operating systems as well as a Microsoft Pro Tablet version of HEED. In addition, numerous supporting documents and tutorials are also available on the web site. Specifically, the following activities make possible the transfer of this technology:

- All software and supporting documents developed under the project are available to download for free from the UCLA Energy Design Tools web site (http://www.energy-design-tools.aud.ucla.edu/).
- A user Hotline is maintained with response to all technical queries within 24 hours.
- In addition, Twitter and Facebook pages were created to help users communicate with each other and keep up to date on new developments.
- Our EnergyDesignTools web site also has links to YouTube tutorials on HEED and Climate Consultant, in both English and Spanish.

- The web site, Hotline and all software developed through this project will be maintained for at least three years after the completion of the grant.
- A series of live Workshops and Demos have taken place, most recently at the PLEA (Passive and Low Energy Architecture) Conference at the Biltmore Hotel in Los Angeles, July 10, 2016 which covered HEED and Climate Consultant in detail, plus brief demonstrations of SBEED and OPAQUE.

CHAPTER 6: Production Readiness Plan

The goal of the plan is to determine the steps that will lead to the manufacturing of the technologies developed in this project or to the commercialization of the project's results.

6.1 Production Readiness Plan for Phase Change Materials

Integrating microencapsulated PCMs into cementitious systems is convenient and will not require much additional development on the part of concrete producers, as the PCM microcapsules can simply be added directly to concrete mixes. Indeed, full-scale structures with PCM-concrete composite envelopes have already been constructed (Cabeza et al., 2007, Castell et al., 2010). Furthermore, microencapsulated PCMs are currently on the market and available from several manufacturers, including MicroTek Laboratories (http://www.microteklabs.com), Micronal (www.micronal.de), and PureTemp (www. puretemp.com). These manufacturers are able to produce microencapsulated PCMs with a wide range of melting temperatures by blending paraffin with different alkane chain lengths.

The biggest hurdle to widespread use of microencapsulated PCMs in buildings is the cost of the PCMs. Currently, the cost of bulk microencapsulated PCM is over $10/kg (MicroTek), whereas the results of Task 2.7 estimated that the price of PCM must be below $1/kg to ensure a payback period of less than 10 years. Therefore, the current cost of microencapsulated PCMs is prohibitive, and must be reduced if PCM-concrete composite envelopes are to be economically feasible for use in buildings.

6.2 Production Readiness of Software Tools

While the software products developed under this project are available to the general public for free, the software must be as robust as any commercial software. As a result, each software product developed has had a thorough Beta testing by the development team and a set of advanced and beginning users. Each program has a commercial quality Install procedure available to download from the UCLA Energy Design Tools website. The software includes HELP and DEMO options as well as YouTube Tutorials. A user Hotline is maintained with response to all technical queries within 24 hours.

Although the software will be freely available it has commercial implications for evaluating the energy impact of existing and new building material (such as the PCM discussed in Chapter 2).

GLOSSARY

Term	Definition
AB32	California's Global Warning Solutions Act of 2006 which set an absolute statewide limit on greenhouse gas emissions, and confirmed California's commitment to transition to a sustainable, clean energy economy
Admittance method	Well-known method that allows one to estimate time lags and a gradual decrease in quality or quantity (decrement) factors for building envelopes based on the thermal properties of the envelope
ASHRAE Standard 140	ASHRAE Standing Standard Project Committee 140 is a standard method of test for the evaluation of building energy analysis computer programs
Climate Consultant	A design tool which helps users make best use of local climate conditions
Decrement Factor	The proportional reduction or damping in a heat wave as it moves through a High Mass material, beyond that accounted for by U value alone. The greater the mass, the greater the dampening of the heat wave
Effective medium approximation	Theoretical model that predicts the effective properties of a composite material based on the proportions and properties of the constituents
Energy Indicator (EI)	A figure of merit to evaluate the thermal performance of PCM-composite building materials that can be measured conveniently in the laboratory
EnergyPlus	A whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings (https://energyplus.net)
Figure of Merit	A quantity used to characterize the performance of a device, system or method, relative to its alternatives
GHG	Greenhouse Gas is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range
Heat Gain/Heat Loss	The rate of heat transfer through a wall, roof, floor, or slab measured in BTU per hour, taking into account air temperature, incident solar load, convection at the outdoor and indoor surfaces, and conduction through the wall as modified by time lag and decrement factor

Term	Definition
HEED	Home Energy Efficient Design, an early-stage residential design tool
HERS BESTEST	Home Energy Rating System Building Energy Simulation Test
Microencapsulated phase change materials (PCM)	PCMs contained within small microcapsules with a polymeric shell (e.g., made of melamine-formaldehyde) so as to increase stability and prevent chemical reaction with the cement paste matrix
Model predictive control (MPC)	Temperature control method that uses a thermal model of the building along with future weather predictions to heat/cool the building accordingly
Mortar	A composite consisting of inclusions (e.g. microencapsulated PCMs, quartz sand) embedded in a cement paste matrix
OPAQUE	Software tool
Payback period	Estimated time required to recoup the cost of adding microencapsulated PCM to a building envelope – i.e., the time at which the accumulated cost savings from reduced energy consumption is equal to the estimated cost of the quantity of PCM within the wall
PCM	Phase Change Materials can increase the thermal mass of building envelopes by storing large amounts of thermal energy owing to their latent heat of melting and solidification
PCM dosage	The amount of PCM in a PCM-mortar composite material, usually given as a volume fraction (vol. %)
SBEED	Small Building Energy Efficient Design, a first-step energy analysis and design tool for non-residential small buildings
Total Equivalent Temperature Difference (TETD)	The hypothetical temperature difference used to determine heat gain/loss through surfaces with thermal mass. It accounts for the periodic variation of sol-air temperature and for the time lag and decrement factor as this surface temperature moves through the building envelope
Thermal model	Mathematical model used to simulate heat transfer and the change in temperature over time within a domain (in this case, a PCM-composite wall or cylinder)
Time Lag	The number of hours it takes a temperature wave to move from a walls outside surface to its inside surface
Title 24	California Energy Commission's California Building Standards Code

Term	Definition
U Value	The heat loss coefficient for any combination of materials that make up part of the building envelope. It equals the number of BTUs per hour that pass through one square foot of the building envelope for each degree difference between the inside and outside temperatures.
ZCB	Zero Carbon Building has zero net energy consumption or zero net carbon emissions on an annual basis
ZNE	A ZNE Code Building is one where the value of energy produced by on-site renewable energy resources is equal to the value of the energy consumed annually by the building, at the level of a single "project" seeking development entitlements and building code permits, measured using the California Energy Commission's Time Dependent Valuation metric. A ZNE Code Building meets an Energy Use Intensity value designated in the Building Energy Efficiency Standards by building type and climate zone that reflect best practices for highly efficient buildings

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